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The effect of shear strength on the ballistic response of laminated composite plates

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ABSTRACT

The ballistic performance of clamped circular carbon fibre reinforced polymer (CFRP) and Ultra High Molecular Weight Polyethylene (UHMWPE) fibre composite plates of equal areal mass and 0/90° lay-up were measured and compared with that of monolithic 304 stainless steel plates. The effect of matrix shear strength upon the dynamic response was explored by testing: (i) CFRP plates with both a cured and uncured matrix and (ii) UHMWPE laminates with identical fibres but with two matrices of different shear strength. The response of these plates when subjected to mid-span, normal impact by a steel ball was measured via a dynamic high speed shadow moiré technique. Travelling hinges emanate from the impact location and travel towards the supports. The anisotropic nature of the composite plate results in the hinges travelling fastest along the fibre directions and this results in square-shaped moiré fringes in the 0/90° plates. Projectile penetration of the UHMWPE and the uncured CFRP plates occurs in a progressive manner, such that the number of failed plies increases with increasing velocity. The cured CFRP plate, of high matrix shear strength, fails by cone-crack formation at low velocities, and at higher velocities by a combination of cone-crack formation and communition of plies beneath the projectile. On an equal areal mass basis, the low shear strength UHMWPE plate has the highest ballistic limit followed by the high matrix shear strength UHMWPE plate, the uncured CFRP, the steel plate and finally the cured CFRP plate. We demonstrate that the high shear strength UHMWPE plate exhibits Cunniff-type ballistic limit scaling. However, the observed Cunniff velocity is significantly lower than that estimated from the laminate properties. The data presented here reveals that the Cunniff velocity is limited in its ability to characterise the ballistic performance of fibre composite plates as this velocity is independent of the shear properties of the composites: the ballistic limit of fibre composite plates increases with decreasing matrix shear strength for both CFRP and UHMWPE plates.

1. Introduction

Structures made from fibre composites are finding increasing application in light-weight ships, vehicles and aircraft. In addition to their structural performance, ballistic resistance may also be a requirement. The projectiles might be fragments and other such threats that are directed at vehicles in military applications, or fragments from roads or runways and other debris in commercial and civilian applications. The fibre composites used for ballistic applications are typically Carbon Fibre Reinforced Polymer (CFRP) composites which primarily serve a structural function but also are expected to provide ballistic protection. Kevlar and other aramid composites, and more recently composites made from Ultra High Molecular Weight Polyethylene (UHMWPE) fibres, are increasingly used for impact resistance but these tend to be parasitic in weight and serve little structural function.

Ultra High Molecular Weight Polyethylene (UHMWPE) fibres were commercialised in the late 1970s by DSM Dyneema, NL under the trade name Dyneema® and more recently by Honeywell in the USA under the name Spectra. Both fibres have densities less than that of water ($\rho_f = 970$ kg m^{-3}) and tensile strengths in excess of 3 GPa (Hearle, 2001; Vlasblom and Dingenen, 2009). Their very high specific strength has led to their use in high performance sails, fishing lines and marine mooring cables, and woven fabrics are used to make protective gloves. A rationale for their use in ballistic applications has been presented by Cunniff (1999). Cunniff (1999) argued that the ballistic limit of fibre composites scales linearly with the so-called Cunniff velocity c^* of the fibre as defined by

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$$c^* = \left(\frac{\sigma_f \varepsilon_f}{2\rho_f}\sqrt{\frac{E_f}{\rho_f}}\right)^{1/3} \quad (1)$$

where σ_f and ε_f are the tensile failure strength and failure strain of the fibres respectively, while E_f is the tensile modulus of the fibres. Candidate ballistic materials are plotted in Fig. 1 using axes of specific energy absorption and longitudinal wave speed. Contours of constant Cunniff velocity c^* are included in this plot. This metric suggests that Dyneema® fibres (SK60, SK76, etc.) and Spectra® fibres considerably outperform most other fibres including Kevlar and armour steels, supporting their use in ballistic applications.

A number of studies have been conducted to measure the static (Wilding and Ward, 1978, 1981, 1984; Jacobs et al., 2000; Govaert and Lemstra, 1992; Peijs et al., 1990; Govaert et al., 1993; Kromm et al., 2003; Dessain et al., 1992) and dynamic response (Huang et al., 2004; Koh et al., 2008, 2010; Benloulo et al., 1997) of UHMWPE fibres and composites. For example, Russell et al. (2013) have observed that UHMWPE composites have tensile strengths of a few GPa and a shear strength on the order of a few MPa. Moreover, they found that the tensile strength of UHMWPE fibres displays nearly no strain rate dependence for strain rates up to 10^3 s^{-1}. Such measurements have been used to develop continuum models (Grujicic et al., 2009, 2009a; Iannucci and Pope, 2011) to enable the modelling of penetration resistance of UHMWPE composites. Penetration calculations performed using such constitutive models (Frissen, 1996; Grujicic et al., 2009, 2009a; Iannucci and Pope, 2011) are able to reproduce observations to varying degrees of success but typically give little insight into the physical basis of the scaling relation as proposed by Cunniff (1999). In an elegant analytical study, Phoenix and Porwal (2003) demonstrated that the ballistic limit of composite plates scales with c^* by assuming a membrane stretching deformation and failure mode of the impacted plate.

There is now growing anecdotal evidence that the matrix shear strength (which governs the inter-laminar shear strength) and the consolidation pressure affect the ballistic performance of UHMWPE composites. For example, Greenhalgh et al. (2013) have recently reported a highly detailed fractography study that illustrates the effect of consolidation pressure and shear strength upon the energy absorption and failure mechanisms such as delamination and splitting. However, matrix shear strength does not affect the value of c^* and so any observed dependence of ballistic limit upon shear strength violates Cunniff scaling. On the other hand, Wei et al. (2013a, 2013b) illustrated inter-lamina delamination is the major material damage mechanism in E-glass/vinylester composite panels while performing a numerical calculations to study their underwater blast response. To date, no systematic studies that quantify the effect of shear strength upon the deformation and penetration response of composite plates have been reported. This study attempts to address this gap in the literature.

We choose two 0°/90° composite laminates with a wide range of matrix shear strength: (i) CFRP and (ii) Dyneema® UHMWPE laminate. In each case we vary the shear strength of the composite by changing the matrix properties while keeping the fibre type, volume fraction and thereby the value of c^* fixed. This enables us to investigate whether the Cunniff velocity is sufficient to characterise the deformation and penetration responses of these composites. Results are also presented for the impact response of stainless steel plates of equal areal mass in order to provide a baseline comparison.

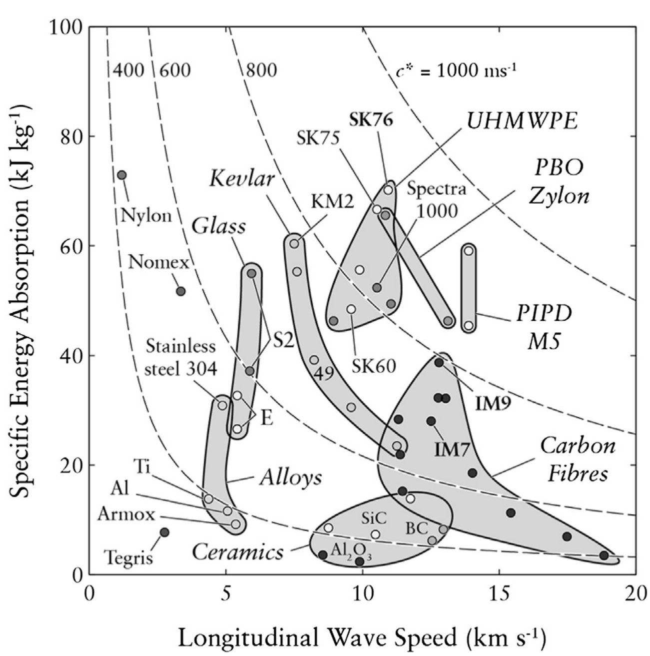

Fig. 1. Materials typically used for ballistic protection applications plotted in longitudinal wave speed – specific energy absorption space. Contours of constant Cunniff velocity c^* are included to indicate the best ballistic materials.

Table 1
Constituent and construction details for the four laminate material systems.

Laminate	Fibre	Matrix	Lay-up & thickness h	Fibre volume fraction V_f
HB26	SK76 Ø17.0 μm	Polyetherdiol-aliphatic diisocyanate polyurethane	$[0°/90°]_{48}$ $h = 6$ mm	0.83
HB50	SK76 Ø15.7 μm	Styrene-isoprene-styrene triblock copolymer	$[0°/90°]_{54}$ $h = 6$ mm	0.82
CFRP-C	IM7 Ø 5 μm	Epoxy fiberite 934 (cured − 2h@120 °C, 6 Bar)	$[(0°/90°)_7 0°]$ $h = 3.75$ mm	0.55
CFRP-U	IM7 Ø 5 μm	Epoxy fiberite 934 (uncured)	$[(0°/90°)_7 0°]$ $h = 4$ mm	0.55

2. Materials and properties

Two types of fibre laminates are investigated: (i) UHMWPE laminates as manufactured by DSM[1] and (ii) CFRP laminates as manufactured by Hexcel Composites Ltd.[2] Two variants of each of these composites were employed and their designations, fibre and matrix types, lay-ups and volume fraction V_f of fibres are listed in Table 1. A brief description of the manufacturing route for these composites is now presented.

2.1. DSM Dyneema composites

Two types of 0°/90° laminates, with commercial designations HB26 and HB50, were procured from DSM. The two composites are similar in most respects, as seen in Table 1; however, the polyurethane matrix in HB26 harder than the Kraton rubber matrix in the HB50 composite. The composites are manufactured in 3 steps:

Step I: Fibres are produced by a gel-spinning/hot drawing process (Smith et al., 1979, 1980). The UHMWPE is dissolved in a solvent at a temperature of 150 °C and the solution is pumped through a spinneret containing a few hundred capillaries in order to form liquid filaments. These liquid filaments are then quenched in water to form a gel-fibre. The gel-fibre is drawn at a

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[2] Hexcel Composites Ltd., Ickleton Road Cambridge CB22 4QD.